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WATER MASSES AND SALINITY

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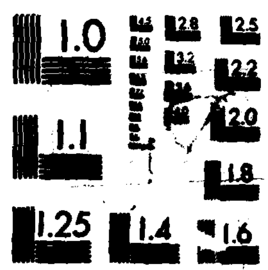
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PYRMONT, N.S.W.

AD-A186 948

RANRL TECHNICAL MEMORANDUM
No. 3/87

OCEANOGRAPHIC FEATURES OF THE EAST AND SOUTH-EAST INDIAN OCEAN FOR JUNE 1983 (U)

by

L.J. HAMILTON

Technical Memoranda are of a tentative nature, representing the views of the author(s), and do not necessarily carry the authority of the Laboratory

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DEFENCE SCIENCE AND TECHNOLOGY ORGANIZATION
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RAN RESEARCH LABORATORY

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OCEANOGRAPHIC FEATURES OF THE EAST AND SOUTH-EAST INDIAN OCEAN FOR JUNE 1983 (U)

L.J. HAMILTON

ABSTRACT

During the period late May to late June 1983 two research vessels and seven ships of opportunity transited sections of the south-east and east Indian Ocean. Expendable bathy-thermographs were deployed and several Nansen stations occupied, providing a rare occasion of widespread quasi-synoptic data coverage for this area. Satellite imagery is available from two sources and three satellite tracked drifting buoys were in the area. Data are used to form a broad scale description of oceanographic conditions for the period, with more detailed analysis possible in the area north-west of Australia. Comparisons are made with data from the Indian Ocean Expedition of the early 1960s and other sources. The relation of surface thermal patterns to circulation is examined.

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INTRODUCTION

An unusual occurrence of widespread oceanographic data coverage in the eastern Indian Ocean (Fig. 1, Fig. 2) has made possible a limited regional description of temperature and current structure for June 1983. The area north west of Australia is to be the subject of intensive effort during 1986-87 in the LUCIE project (Harden-Jones and Godfrey, 1985). Data discussed here have coincidentally been obtained over a similar area, and may provide a useful adjunct to the data base for the LUCIE study. Little work has been done in this area since the International Indian Ocean Expedition (IOE) cruises more than 20 years ago (e.g. Wyrtki, 1971). The IOE cruises were the basis for establishing much of the known oceanography of the Indian Ocean. The Indian Ocean is not completely known however, as witnessed for example by the comparatively recent recognition of the Leeuwin Current off south-western Australia (Cresswell and Golding, 1980).

Some features of the Indian Ocean have been well established by the IOE cruises, but many descriptions were based on data combined from cruises undertaken over several years, and for extended seasons. Good data coverage was obtained in the present study off north western Australia over a period of one week, with wide coverage over other areas in a two week period.

The aim of the present analysis is to build up as coherent a picture of oceanographic features for the east Indian Ocean as the data will allow, and compare the results with historical data sources. The data discussed also provide an opportunity to assess the usefulness of satellite imagery in determining flow patterns and thermal structure for the east Indian Ocean. With the advent of routine satellite data acquisition in

oceanography, sea surface temperature (SST) patterns and their relation to circulation and subsurface structure are of some interest. Buoy data will be compared with circulation patterns and current speeds deduced from Nansen station and XBT data. A 'first-look' data analysis has previously been given in Hamilton (1985), when tabulating the Nansen station data taken during RANRL cruise 23/83. The availability of more data from buoys and expendable bathy-thermographs now allows a fuller analysis.

DATA AND METHODS

Cruise tracks and dates are shown in Fig. 1. The time span of the ship data is 21 May to 30 June 1983 with most data for 23 May to 15 June. HMAS Cook and FRV Soela are oceanographic research vessels of the Royal Australian Navy (RAN) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), respectively. MV ANRO Australia is a merchant ship fitted by CSIRO with an XBT launcher (Greig and others, 1986). Other vessels are ships of the RAN, namely HMA Ships Adelaide, Canberra, Moresby, Swan, Torrens, and Yarra. Sites of Nansen stations, expendable bathy-thermographs (XBTs) and buoy tracks are shown in Fig. 2, (and Fig. 9). Buoy data are from Cresswell (1985). Depth of buoy drogue is 20 m. Nansen station temperature and salinity data are listed by Hamilton (1985), together with temperature-depth cross-sections, some satellite imagery, and a 'first look' data description. Details of FRV Soela cruises are described by Leech (1983), and Stevens (1983). The XBTs are Sippican type T4, nominally usable to 450 m. NOAA (United States National Oceanic and Atmospheric Administration) infra-red (i.r.) satellite imagery was received by the Western Australian Institute of Technology (WAIT), and Geostationary Meteorological Satellite (GMS) i.r. imagery received twice daily by Macquarie University, Sydney. The imagery is mostly for areas east of 110°E., and is often cloud covered.

The measurement period coincides with the south-west monsoon, described by Wyrtki (1962a) as a time of more vigorous atmospheric and oceanic circulation than the north-east monsoon, which subsides in April.

Contour diagrams of horizontal circulation and thermal patterns have been constructed from the data. Cross-sections of parameters are also

used, as are plots of temperature versus salinity (T-S plots). Comparisons of surface and subsurface patterns are made where possible, and some water mass movements traced. An intensive XBT survey was made by HMAS Cook in the area north-west of Australia, together with 12 Nansen stations occupied nominally to 1500 m. Niskin stations were occupied south of this area by FRV Soela. Coverage in other areas is sparse and less synoptic.

SEA SURFACE TEMPERATURE (SST)

Patterns of SST drawn from XBT data are shown in Fig. 3. Weak frontal structure is seen from 21°S., 103°E. to Fremantle, with isotherms becoming parallel in a stronger frontal region along the coast. The Leeuwin Current can clearly be seen in both NOAA and GMS imagery as a streamer of warmer water from north of Shark Bay to the Great Australian Bight, and is reflected in the XBT data as warm waters along the coast. It appears widest north of Shark Bay.

Warm patches of water at or near a temperature of 28°C occur near 16°S., 119°E. and 13°S., 115°E. These waters are over 70 m deep, but horizontal extents are not well defined. The 119°E. patch appears in cross-sections to be a warm pool or eddy, to the south of the South Equatorial Current (SEC). Relatively cooler waters (less than 27°C) occur to the south and west of Sumba. In contrast the warmest waters (over 29°C) are seen to the west at roughly the same latitude, south-west of Java. The cooler waters are perhaps caused by upwelling on the northern border of the South Equatorial Current, as described by Wyrtki (1962b). Little thermal relief is seen over much of the northern area, including the area north-west of Broome, a data intensive area. GOSSTCOMP (Global Operational Sea Surface Temperature Computation, a NOAA product) charts for the weeks ending 7 and 14 June also show little thermal relief.

Except in the north-west, GOSSTCOMP isotherms agree closely with those shown here in position, but roughly south of 15°S are low by 1°C. The GOSSTCOMP charts could therefore be used with a fair degree of confidence to fill in areas where ship data are scarce. Two or three of the weekly GOSSTCOMP charts should be used, to check for self consistency from one period to the next, since shifting patterns of cloud coverage can cause apparent changes in satellite derived SST.

Cooler water at less than 25°C indicative of upwelling is seen in the Port Hedland area, in FRV Soela data and HMAS Cook engine room inlet temperatures, and is also seen in the GOSSTCOMP charts. Macquarie University GMS imagery shows it to occur in a band along the coast from Port Hedland to Broome. Salinity data from FRV Soela supports the idea of upwelling, with higher salinity near the coast, and isohalines tilted upwards. The upwelling is seen in the imagery over the whole analysis period.

COMPARISONS OF SST WITH HISTORICAL SST DATA

The general SST patterns and ranges are typical of those shown in sources for this period of the year, e.g. Tchernia, 1980 (plate 16). The frontal structure about 25-27°S., 108-110°E. corresponds in location with the northern boundary of a cyclonic current loop described by Wyrtki (1962a) as a permanent feature of the circulation. The SST frontal pattern appears to be the surface expression of this dynamic feature. Infra-red imagery (e.g. Legeckis and Cresswell, 1981) (plate 1) appears to show a clear front visible between warm northern and colder southern waters in this area, i.e. the cyclonic loop can be detected in SST patterns. The cyclonic loop is also suggested in a WAIT infra-red image for 25 May 1983. Other imagery is cloud covered.

Rochford (1962, Fig. 5 for July-October) also found cooler northern waters at less than 27°C, and a warm area over 27°C near 13-15°S., 118°E. for the period July to October, corresponding to the warm patch shown here at 28°C. The cooler waters shown by Rochford extend eastward in a tongue along 12°S., 120-122°E., as they do here. The warm patch at 13°S., 115°E. corresponds to a region of high temperature shown by Rochford extending westward from the Australian coastline along 12°S. Waters with temperature less than 27°C near the coast at 15°S., 125°E. also correspond to a cooler area less than 27°C shown by Rochford, which in his maps is connected to the northern cooler waters already mentioned. The GOSSTCOMP chart ending 14 June (but not 7 June) also shows cooler waters from the coast to Timor, in a pattern very similar to that of Rochford. These are striking similarities and indicate a remarkable constancy in the surface thermal regime for this period of the year in both temperature and position of isotherms, although two sets of measurements taken 20 years

apart hardly constitute a time series. SST in the north varies by only two or three degrees all year round e.g. Tchernia (1980) (plates 15, 16) which could explain some of the apparent constancy, but not all. The similarities are likely to be related to the dynamics of the area for this period.

The locations of the two warm patches found here, and the warm pattern shown by Rochford, are explained by the South Equatorial Current (SEC) carrying waters westward along and north of 13°S, with a current component advecting waters south. Surface circulation discussed later shows such a pattern. The source area for the warmer waters appears to be north-west of Australia, perhaps a remnant of summer heating. Rochford (1969) attributes colder water at all depths to 300 m and deeper north of 14°S to be due to dynamic uplift along the northern boundary of the SEC.

Mild upwelling in the same area discussed here off Broome was noted by Rochford (1962, Fig.17) at temperatures of 25-27.7°C and salinity 34.50 to 35.00 practical salinity units. The lower temperature limit here is 24.4°C, with upper salinity limit of 35.2. The upwelling seen here extends farther south-west along the coast than observed by Rochford. Macquarie infra-red imagery also suggests upwelling in another area where it was observed by Rochford, north of Wyndham.

TEMPERATURE AT 250 METRES DEPTH (T250) (Fig.4).

The frontal structure from 21°S., 103°E. to Fremantle is seen in T250 but more strongly. This indicates that the SST frontal pattern is indeed related to subsurface structure. Warmer water north-west of Geraldton is shown by several temperature cross-sections (Hamilton, 1985) to result from an eddy, or meander structure. Cooler waters south of Sumba correspond to the cooler SST seen there also i.e. the cooler waters are not merely a surface phenomenon. There is considerably more structure in T250 in the north-west area than for SST. The structure is complex but comparison with dynamic topography does yield a consistent pattern for circulation. This is discussed later.

WATER MASSES AND SALINITY

Several water masses can be identified from temperature and salinity properties alone, but others can only be tentatively identified without oxygen or other information. A cross-section of salinity for the southern stations (Fig. 5) shows Antarctic Intermediate Water (a salinity minimum) at 900 m, and South Indian Central (SIC) waters (a salinity maximum) from the surface to deeper than 125 m. A front in surface salinity between stations 4 and 5 is seen to be caused by subtropical SIC water underlying less saline surface water, a phenomenon described by Rochford (1969).

Sea surface salinity data (Fig. 6) are available only at Nansen/Niskin station sites. Highest surface salinity (35.91) occurs at station 2(26°17'S, 108°01'E), and lowest surface salinity (34.13) south of Sumba, in conjunction with the lower SSTs there. For the few data points available surface salinity tends to reflect the same pattern as for SST.

T-S curves are shown in Fig. 7, with water masses (after Rochford, 1969). Northern and southern stations are seen to lie in different T-S regimes above 500 m depth. Profiles of salinity, temperature, and density (Hamilton, 1985) also show characteristics pointing to water masses. Elevated temperatures at 600 to 700 m and a corresponding deviation in the density profile for stations 1, 2, and possibly 4 and 6 may be caused by low salinity waters of the subtropical oxygen maximum drifting north on about the 26.80 sigma-t surface. Stations 7, 8 and 9 show a salinity maximum at 200 m of 34.78, 34.78 and 34.66 (with sigma-t of 25.33, 25.86, 25.67) consistent with Rochford's definition of the tropical oxygen minimum. Stations 11 to 15 have the same water type below about 100-200 m, with salinity varying little below 200 to 300 m.

Rochford (1969) describes this "vertically homogeneous zone as part of the Equatorial Frontal Zone extending across the south Indian Ocean as a structural feature of the South Equatorial Current". Temperature cross-sections (Hamilton, 1985) show several correspondences with subsurface salinity structure e.g. separation of isotherms in XBT sections on southern sections is associated with intrusions of high salinity SIC waters. The differing types of data sets (XBT and Nansen station) yield consistent results.

SURFACE CIRCULATION

A detailed picture of the surface circulation (Fig. 8) for the area north-west of Australia and north-west of Fremantle can be built up from buoy data, geostrophic calculations, and temperature cross-sections. In other areas there are no Nansen stations, and the currents inferred from XBT sections alone are ambiguous in direction as explained later.

Temperature sections (Hamilton, 1985) allow the subsurface expressions and extent of some of the currents indicated by buoys to be defined in areas having no Nansen station data. It was hoped that geostrophic calculations of surface current strengths would lead to a level of no motion being found at which the geostrophic and buoy values would agree. However the northern buoys are not near enough to Nansen station data for very close comparisons, and a buoy in the area of the southern stations has opposite general direction of travel to that calculated. These points are discussed later.

Wyrtki (1962a) found that the choice of the depth of level of no motion in the north did not affect the current strengths calculated, for a level of 600 to 800 m or deeper. This is also found here for the northern stations. According to Wyrtki, the South Equatorial Current (SEC) penetrates to about 400 m, with geopotential topographies from 1750 to 400 m very smooth north of 20°S, so that the choice of the depth of the level of no motion is not critical. The level of no motion slopes to 2000 m south of 40°S. "The dynamic topography north of Australia is very smooth indicating absence of distinct circulation at 400 m." This does not preclude a mean flow at 400m.

General results for surface circulation.

Cocos Island to North-west Australia

The South Java coastal current is seen flowing eastwards in temperature sections from MV ANRO Australia, HMAS Moresby, and HMAS Canberra, being stronger in the earlier section. This is consistent with the direction of travel of the buoy west of this area for May to June (Fig. 2). The temperature sections apparently extend to the east the extent of the Java current as defined by the buoy for June. However it is not certain the two currents are in fact the same. Surface currents south-west of Java to Cocos Island are difficult to define from the XBT sections. They generally indicate weak eastwards flow at the surface. However, isotherms below 100 m slope downwards from north to south, as they do in all north to south sections, indicating flow to the west. Whether the westwards flow or the eastwards currents dominate cannot be determined from these data. Hamon (1965) deduced a weak westwards current at 300 m for 15-32°S from a comparison of dynamic topographies of the surface and 300 m level relative to 1750 m.

North East Indian Ocean

North-west of Australia there is a high data density for the period. Comparison is available with data for May 1 - June 12 1961 (Hamon, 1965). There are two dominant features, the SEC flowing to the west at about 14 cm/sec, and a cyclonic circulation at 14 to 17 cm/sec north-west of Broome, relative to 1000 dbar. Average buoy current strength for June to July for an area farther east is roughly 20 cm/sec, and for July to August when nearer the station area is roughly 14 cm/sec. The average buoy speed and geostrophic calculations are in good agreement. The 28°C waters at 13°S., 119°E. appear in cross-section to be a shallow (70 m) pool of

warm waters, having weak anti-cyclonic circulation, and possibly being advected west on the southern boundary of the SEC.

Temperature fields and surface mixed layer depth for the area are shown in smaller scale in Fig. 9, with Hamon's surface dynamic topography and station positions in Fig. 10. It is readily apparent that Hamon's patterns are very similar to those found here, for both directions and strengths of circulation. Diagrams of surface dynamic contrast for the two data sets are practically identical (Fig. 10). For February-March 1962 however, Hamon found an anti-cyclonic circulation in the same area. For July-August 1961 the pattern was similar, but the SEC was very much stronger, and the cyclonic circulation no longer closed. There is therefore no "a priori" reason for the present data and Hamon's data to be expected to show such high correspondence. The contrast in dynamic topography over the area is low, the highest difference between any station pair being 17 dyn.cm. The perpendicular surface-current component between stations 14 and 15 relative to 200 m is 18 cm/sec, indicating flow of the SEC to the south-west.

The circulation pattern deduced from the temperature field at 250 m (Fig. 9) bears a strong relation to surface circulation patterns found from Nansen data. Shallower fields might also show closer correspondence, but this is not investigated. The smoothing effect of the Nansen station separation gives a broad pattern for circulation (Fig. 8) which is seen to be consistent with the more complicated pattern deduced from the T250 field alone.

South of 20°S.

From about 22°S., 103°E., to Fremantle, surface circulation can be well defined. XBT sections from HMAS Cook and HMAS Moresby show stronger

vertical gradients here than in sections farther north, allowing unambiguous inference of current components. There are 6 Nansen stations in the area, although widely spaced. Near the coast, five XBT sections from near Shark Bay to Fremantle allow good definition. The same features are seen in several sections, showing data to be consistent, and allowing horizontal as well as vertical extents to be defined.

The surface flow east of 21°S., 103°E. is generally weak and to the south-east, and has a meandering pattern. Off Geraldton a warm-core eddy or meander is situated, with the HMAS Canberra XBT section showing no weakening of the feature to the limits of the XBT traces at 450 m. The 12°C isotherm at the centre of the feature is over 470 m deep. A second eddy or meander is situated north-west of Fremantle. The 25°C SST isotherm marks the approximate boundary of the weak surface front from about 22°S., 103°E. to Fremantle, which has strong subsurface expression between 200 m and 500 m. Geostrophic current component strengths at the surface relative to 1000 m range from 3 to 12 cm/sec, and agree in direction with currents inferred from the XBT sections. WAIT imagery clearly shows the Leeuwin current flowing south along the coast and into the Great Australian Bight.

A buoy path shown by Cresswell (1984) for May to July 1983 along about 24°S is generally in opposite direction to that given by the stations and XBT sections. This indicates either that the buoy has lost its drogue, that local wind effects on the buoy are over-riding the rather weak currents in this area, or that the depth of no motion is incorrect. Since the XBT derived surface current directions inferred from the temperature field at 250 m and shallower agree with the geostrophic current directions, with assumed level of no motion of 1000 m, the latter seems unlikely. A

current reversal is shown at 150-200 m in this area by the geostrophic calculation relative to 1300 m level of no motion, but the currents above the minimum are much stronger than the currents below.

A subsequent CSIRO report (Metso and others, 1986) describes loss of drogue for the buoy near the end of the track shown on 24 July, when a tilt sensor was activated. It seems likely that the drogue was lost or fouled much earlier.

The currents shown south of 20°S. in the present data are similar to those shown by Wyrtki (1962a) for October-November 1959 and Hamon (1972) for July 1965. Dynamic topography of the sea surface relative to 1300 dbar shown by Hamon for late July (his Fig.1(a)) indicates surface currents largely identical to those inferred here, but not so in other months, where the patterns vary, e.g. being much weaker in March 1966.

SUBSURFACE CIRCULATION

Although the number of Nansen stations occupied is not large, particularly in the south, several distinct subsurface circulation features can be seen. Current profiles (Fig. 11) formed from geostrophic calculations between pairs of southern stations 1 and 2, 2 and 4, 4 and 5, 4 and 6, 2 and 6 show a current maximum (with respect to the surface) at 500 m (see Fig. 2 for station numbers). Station 3 is not used because data were obtained only to 200 m. Using 1300 m as a level of no motion shows that current components reverse in direction between 150 and 200 m between stations 1 and 2, 2 and 4, 4 and 6, 2 and 6, and 1 and 6. The currents at 500 m $\pm$200 m then appear as a weak maximum (1 to 3 cm/sec) in the reverse flow, except between stations 4 and 5 where current components at all depths are in the same direction. This reverse current direction agrees with movement of the subtropical oxygen maximum discussed in the section on water masses.

Northwest of Australia, current profiles (Fig. 11) along north-south sections show little current below 300 to 500 m, and a rapid increase above this level to the surface, the SEC. Hamon (1965) mentions the 'importance of the upper 300 m in determining the surface dynamic topography in tropical and subtropical regions'. East-west sections show much different profiles, with subsurface current maxima, at 150 m between stations 12 and 13, and weakly at 250 m between stations 10 and 11. Subsurface current component reversals occur also. The east-west sections occur north and south of the SEC. The subsurface current component between stations 12 and 13 is to the north and appears by its strength to be a component of the SEC, above which lies a slower flow, or a flow in a different direction, possibly related to the movement of the relatively cooler and less saline surface waters south of Sumba. (i.e. the SEC appears to be flowing to the north-west here, not directly westward.)

The T250 field (Fig. 9) implies highly varying flow over the region, but the broad pattern is consistent with the calculated geostrophic flow. Subsurface currents between stations 10 and 11 calculated from vertical spacing of 50 m are less than 2 cm/sec. Subsurface southward flow between stations 11 and 14 relative to 300 m is effectively at equal current strength of component from the surface to 100 m, weakening to zero at about 200 m, after which a reverse flow is seen to 300 m, with a maximum of only 1 cm/sec at 250 m. The SEC thus appears to flow both westward and south-westward near stations 11 and 14, with the shallower s.w. component possibly reinforcing the cyclonic surface circulation discussed earlier. The weak currents discussed may be in the 'noise' region of geostrophic current calculations, but results do appear to be consistent.

DISCUSSION AND CONCLUSIONS

The observations discussed in this Memorandum represent a further source of information for a little known area subject to large seasonal variations. They also enable comparison with historical data for similarities or large differences in conditions. Scarce subsurface measurements and wide quasi-synoptic data coverage enable limited comparisons to establish the potential usefulness of satellite data for studies of the east Indian Ocean. Buoy data and geostrophic data have been compared. Several data types have been used in the analysis which yield consistent results, establishing a data set of a kind not often available. Not all the data are shown here. Hamilton (1985) presents the temperature cross-sections, Nansen station data, and satellite imagery.

(A) Use of Surface Thermal Patterns To Infer Surface Circulation And Other Features

(i) Between Equator and 20°S

Two sources of satellite imagery used here detected upwelling off the northwest Australian coastline which was seen in sea truth data by two ships. Infra-red imagery should therefore be useful for studying the occurrence of upwelling in this area. The surface thermal patterns shown in Fig. 3 and Fig.9(a) are in general not related to flow patterns, at least not for the spacing of observations discussed here. There is low thermal contrast over much of the east Indian Ocean for June and all year round, making it difficult to detect currents by their surface thermal expressions. The high water vapour content in equatorial regions makes processing of satellite derived SST more difficult than in other latitudes, further exacerbating the problem. Dynamic topographies off north-western

Australia for June show low relief, and therefore low currents. Also, some subsurface currents occur, on which weaker surface currents are superimposed. This may make surface thermal patterns difficult to interpret. It appears that infra red satellite imagery may not be very useful for current (and thermal) studies off north-west Australia, at least for June. There is some indication of the South Java current as a weak SST frontal region.

(ii) South of about 20°S.

Seawards of the Australian coastline, it appears that infra red imagery of SST patterns can be used to deduce surface circulation patterns. Legeckis and Cresswell (1981) have shown that it is possible to study the Leeuwin current along the coast from about 20°S. into the Great Australian Bight using infra red imagery. Hamilton (1984, 1986) made studies of the area 30-35°S., 110-115°E. which strongly suggested that SST patterns were representative of subsurface structure and surface circulation. In the open ocean, current and subsurface structure shown here from about 21°S., 103°E. to shore is found to be reflected in SST patterns. There are in general stronger surface thermal gradients south of 20°S. than in the northern areas, and they are related to subsurface structure.

(B) Use Of Buoys To Follow Surface Circulation.

In the area north west of Australia, both speed and direction of buoy currents and geostrophic derived currents are in good agreement. The currents here were about 1/3 knot. In a much lower current area of 1/5 to 1/4 knot along 23°S., direction of buoy travel was generally opposite to that shown by geostrophic calculations and XBT sections, and may be in error. Whether this is because of loss of drogue, or wind effects over-

riding weak currents is not known, but it is a reminder that surface currents indicated by buoys are also sometimes in need of verification from other sources, particularly in low current areas.

(C) Comparisons of Oceanographic Conditions With Other Data.

The general surface circulations and surface temperature for the entire area discussed here are similar to the general patterns found in the Indian Ocean Expedition data over a more extended time. Since the IOE studies have shown the importance of the regular monsoon cycle in establishing a regular cycle also in the oceanic circulation, this is not very remarkable. What is surprising is that almost identical patterns and results are seen in some areas off north-west Australia, in data for June taken 22 years apart, in both SST and surface dynamic topography (and therefore surface currents). Tchernia (1980) describes this as being one of only two areas in the Indian Ocean (the other is the Bay of Bengal) bearing the stamp of local climatic conditions. The striking similarities in data for the area north west of Australia in June coupled with the fact that dynamics in other periods are found to be different, may indicate that this area also tends to experience a highly regular seasonal cycle, at least in some periods. The similarities occur in areas where they would not normally be expected, i.e. in open ocean areas, not at land mass boundaries for example.

Currents off the north west Australian area are generally believed to be to the north and north-east in February-March and to the west and south-west in August-September (Tchernia, 1980; plates 13 and 14). The cyclonic circulation discussed earlier could therefore arise in the transition period between these two states as a direct result of the current reversals. It remains to be seen whether a regular cycle does exist, or if the similarities are coincidental.

ACKNOWLEDGEMENTS

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REFERENCES

ANDREWS J.C. (1977). Eddy structure and the West Australian Current. Deep-Sea Research, 24, 1133-1148.

ANDREWS J.C. (1979). Eddy structure and the West and East Australian Currents. Flinders Institute of Atmospheric and Marine Sciences, Flinders University of South Australia, Res. Rep. No. 30.

CRESSWELL G.R. (1985). Satellite drifters northwest of Australia. "Time series of ocean measurements", Intergovernmental Ocean. Com. Tech.Ser. No. 30, Vol. 2. UNESCO

CRESSWELL G.R. and GOLDING, T.J. (1980). Observations of a south-flowing current in the southeastern Indian Ocean. Deep-Sea Res. 27A, 449-66.

GREIG M.A., RIDGWAY, K.R., VAUDREY, D.J., and GODFREY, J.S. (1986). M/V 'Anro Australia' Sections: Thermal Profiles in the Eastern Indian Ocean, May 1983 to July 1984.
CSIRO Marine Laboratories Report 174.

HAMILTON L.J. (1984). Statistical Features of the Oceanographic Area Off South-Western Australia with Application to Real-Time Analysis. RAN Research Laboratory Technical Note No. 4/84.

HAMILTON L.J. (1985). Data Report For RANRL Oceanographic Cruise No. 23/83 (May/June 1983 - East Indian Ocean) RANRL Tech.Memo (External) No.7/85.

HAMILTON L.J. (1986). Statistical Features of the Oceanographic Area off South-western Australia obtained from Bathy-Thermograph Data. Aust.J.mar.Freshw.Res. 37, 421-436.

HAMON B.V. (1965). Geostrophic currents in the south-eastern Indian Ocean. Aust.J. mar. Freshwat. Res. 16, 255-71.

HAMON B.V. (1972). Geopotential topographies and currents off West Australia, 1965-69. CSIRO Division of Fisheries and Oceanography Technical Paper No. 32.

HARDEN-JONES R. and GODFREY J.S. (1985) LUCIE - Leeuwin Current Interdisciplinary Experiment. Pamphlet distributed by CSIRO Marine Laboratories, Hobart Tasmania.

LEGECKIS R. and CRESSWELL, G.R. (1981). Satellite observations of sea surface temperature fronts off the coast of western and southern Australia. Deep-Sea Res. 28, 297.

LEECH, G. (1983). FRV 'SOELA' Cruise Summary SO3/83 (Leg 2) CSIRO Marine Laboratories.

METSO, A., WELLS, G.S., VAUDREY, D.J. and CRESSWELL, G.R. (1986). Satellite-tracked Buoy Data, July 1982 to September 1984. CSIRO Laboratories Report 180.

ROCHFORD D.J. (1961). Hydrology of the Indian Ocean. I. The water masses in intermediate depths of the south-east Indian Ocean. Aust.J.mar. Freshw. Res. 12, 129-49.

ROCHFORD, D.J. (1962). Hydrology of the Indian Ocean. II. The surface waters of the south-east Indian Ocean and Arafura Sea in the spring and summer. Aust.J.mar.Freshwat.Res. 13, 226-51.

ROCHFORD D.J. (1964). Hydrology of the Indian Ocean. III. Water masses of the upper 500 metres of the south-east Indian Ocean. Aust. J. mar. Freshwat. Res. 15, 25-55.

ROCHFORD D.J. (1969). Seasonal variations in the Indian Ocean along 110°E, I: hydrological structure of the upper 500 metres. Australian Journal of Marine and Freshwater Research, 20, 1-50.

STEVENS, J. (1983). FRV 'Soela' Cruise Summary SO3/83 (Leg 1) CSIRO Marine Laboratories.

TCHERNIA P. (1980). Descriptive Regional Oceanography. Pergamon Marine Series Volume 3. Pergamon Press.

WYRTKI K. (1962a). Geopotential topographies and associated circulation in the south-eastern Indian Ocean. Aust.J.mar.Freshwat. Res. 13, 1-17.

WYRTKI K. (1962b). The Upwelling in the Region between Java and Australia during the South-east Monsoon. Aust.J.mar.Freshwater Research. 13, 217-225.

WYRTKI K. (1971). Oceanographic Atlas of the International Indian Ocean Expedition. National Science Foundation. US Government Printing Office, Washington D.C., 20402 USA.

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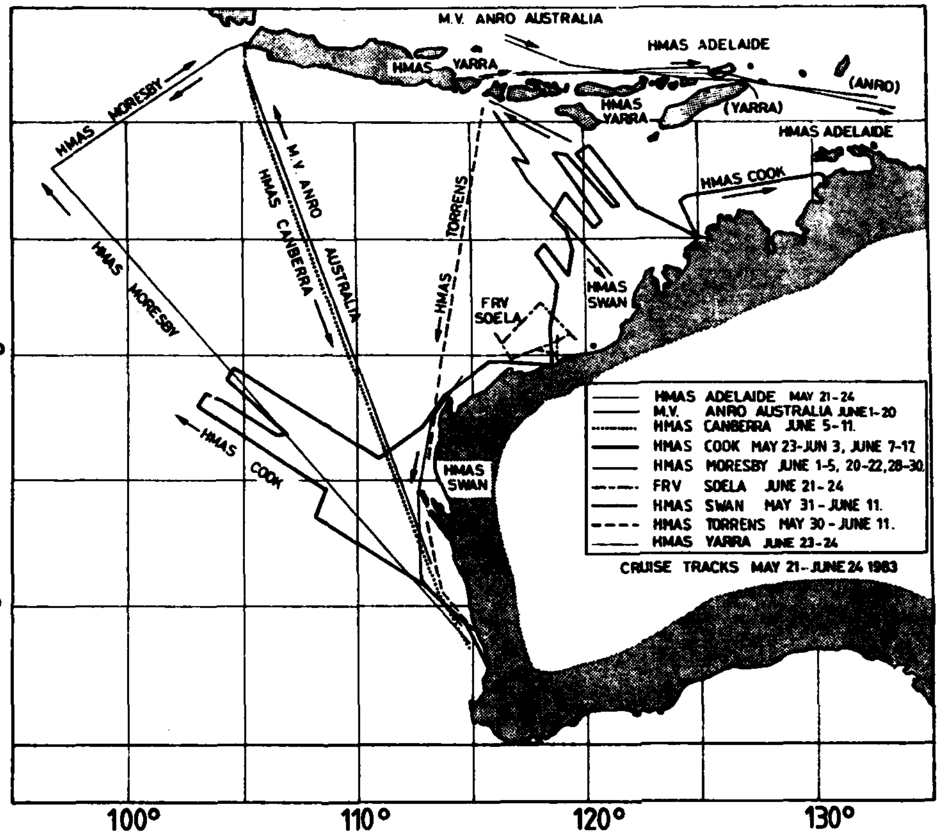
Fig. 11 Geostrophic current profiles relative to the surface between station pairs in the east Indian Ocean for late May and June 1983. Station positions are shown in Fig. 2. See Fig. 8 for surface current directions.



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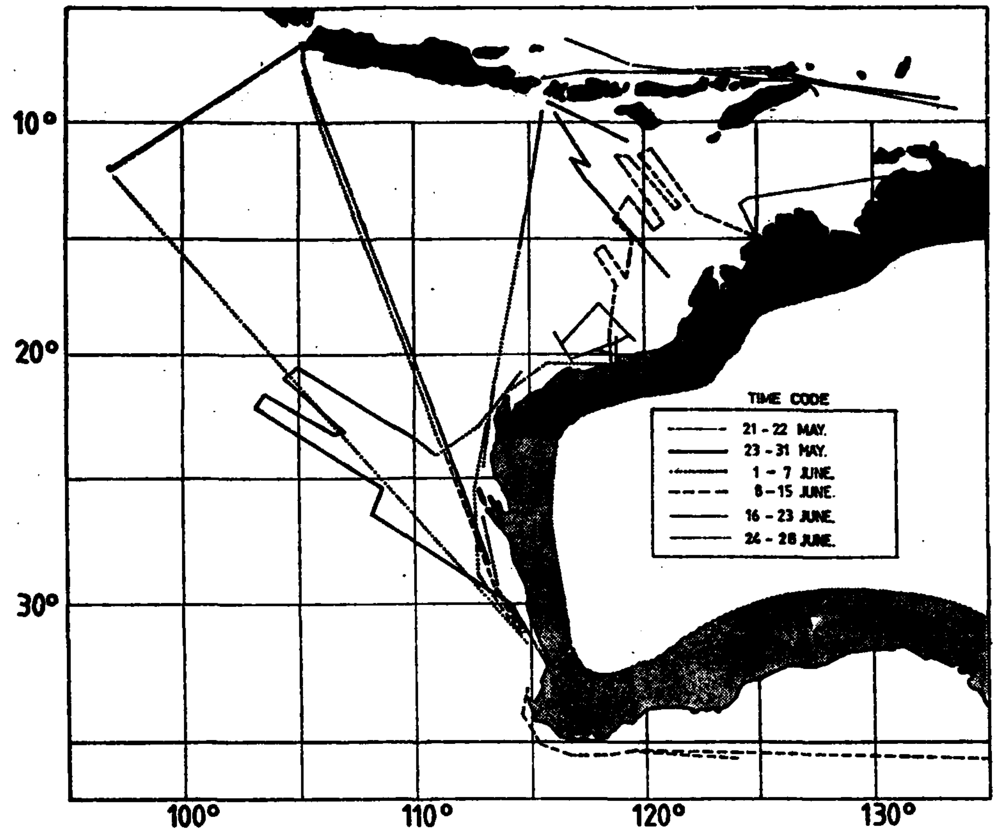

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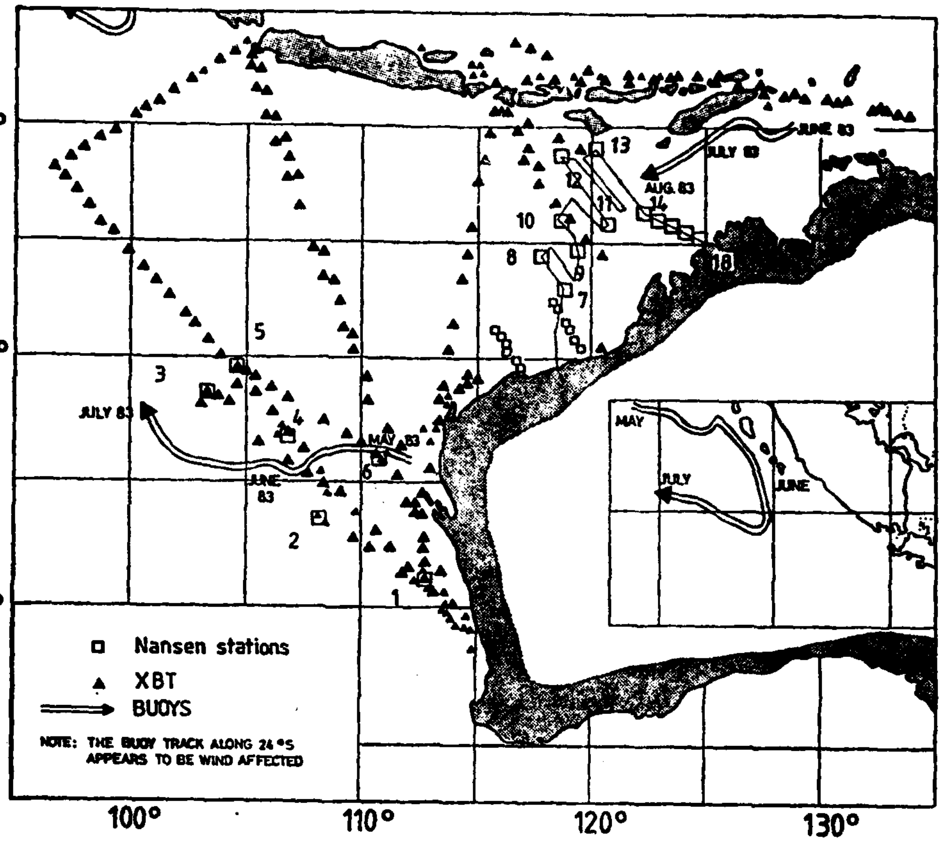

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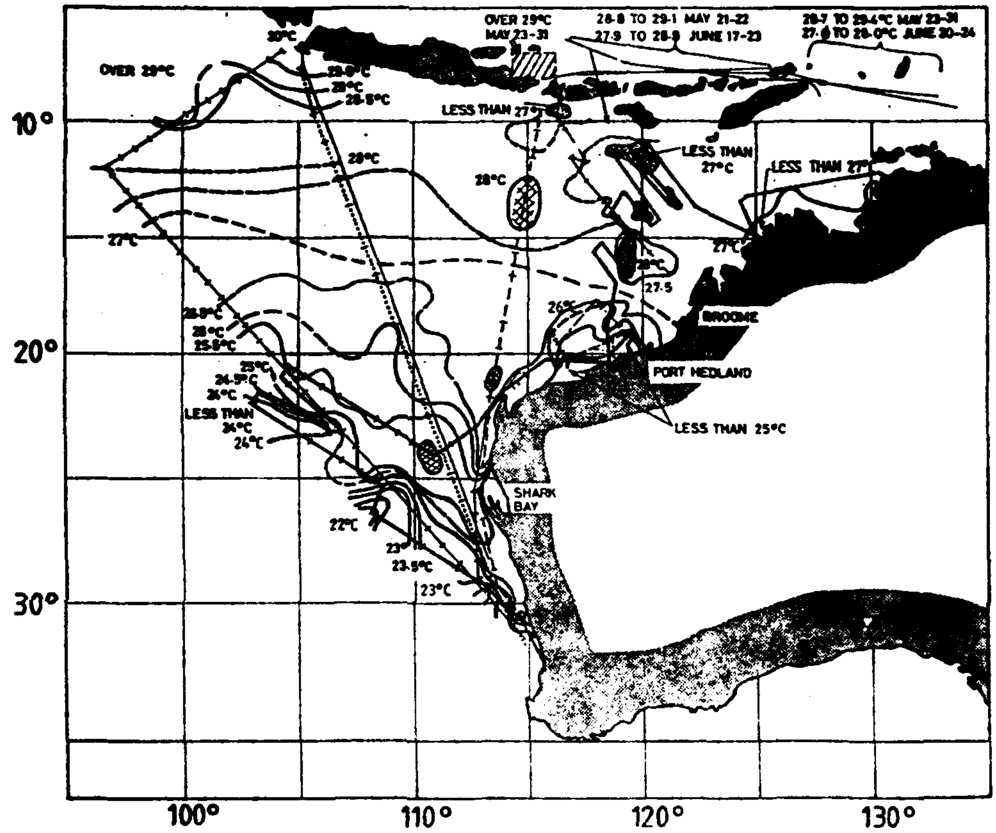
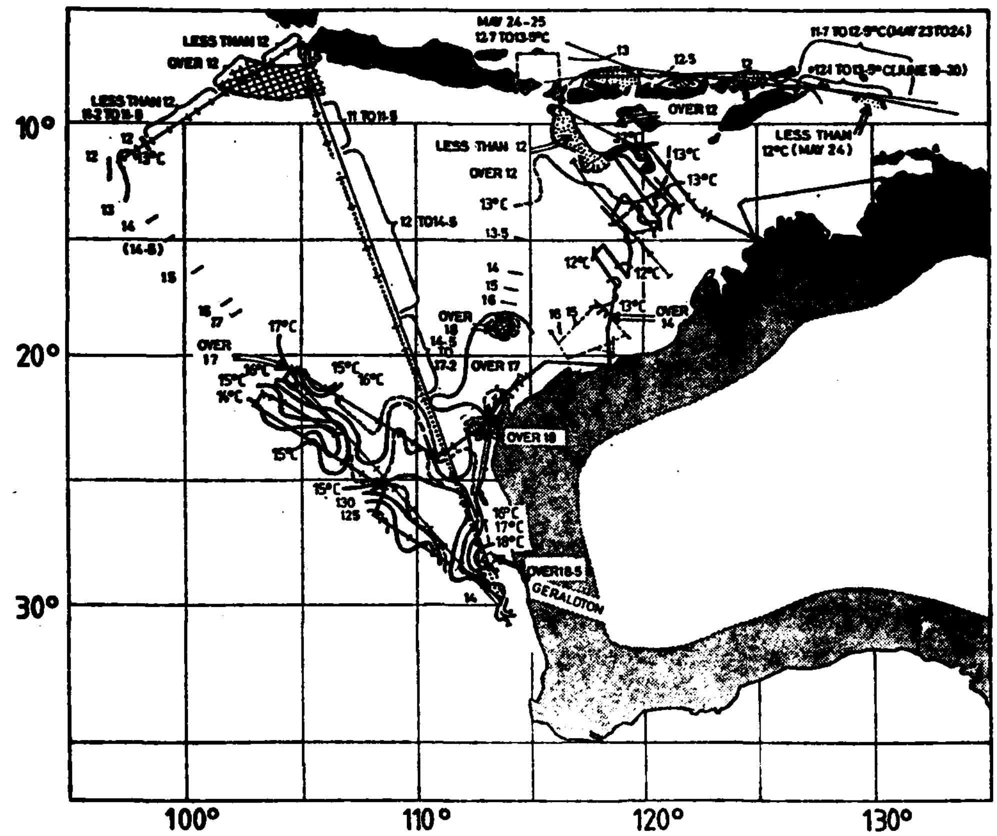


Fig. 3 Sea surface temperature contours in the east Indian Ocean for late May and June 1983 drawn from XBT data. Cruise tracks are also shown.



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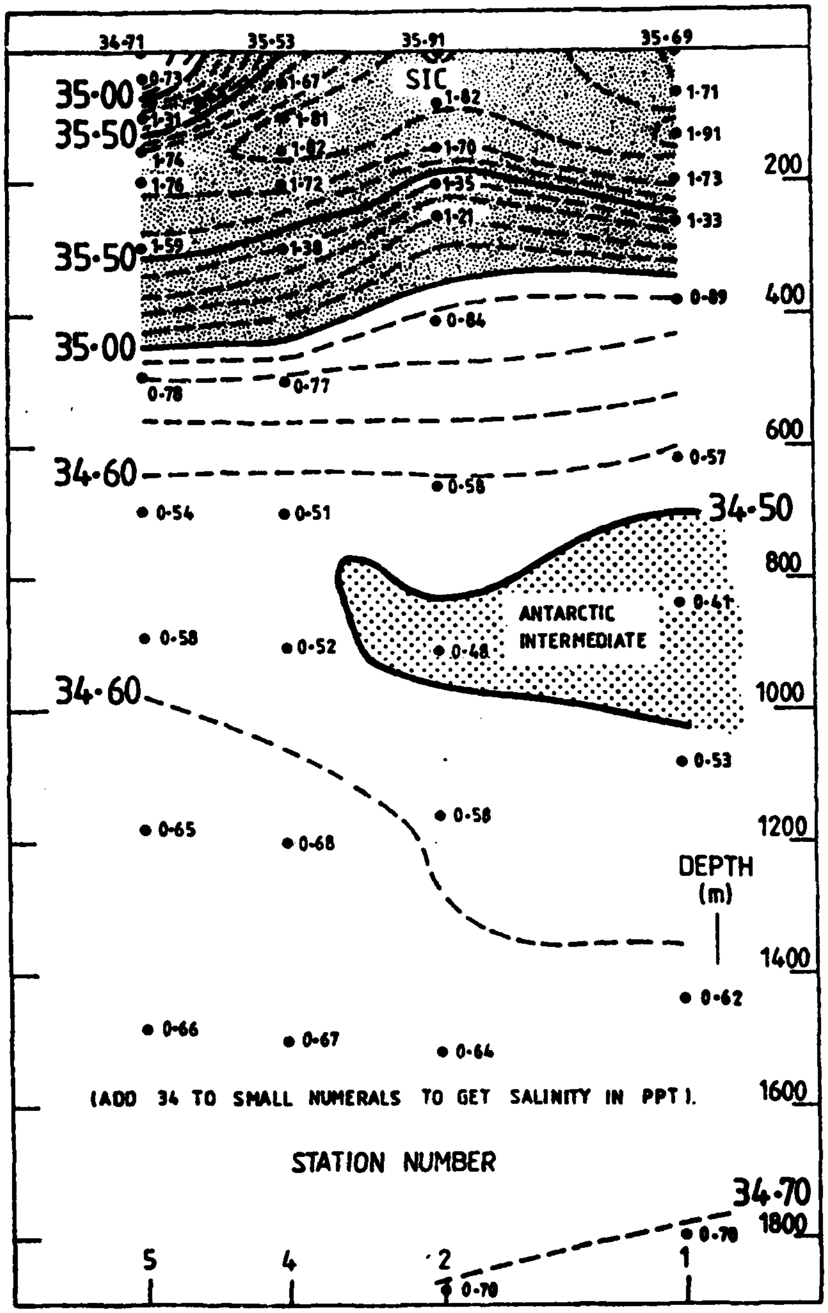

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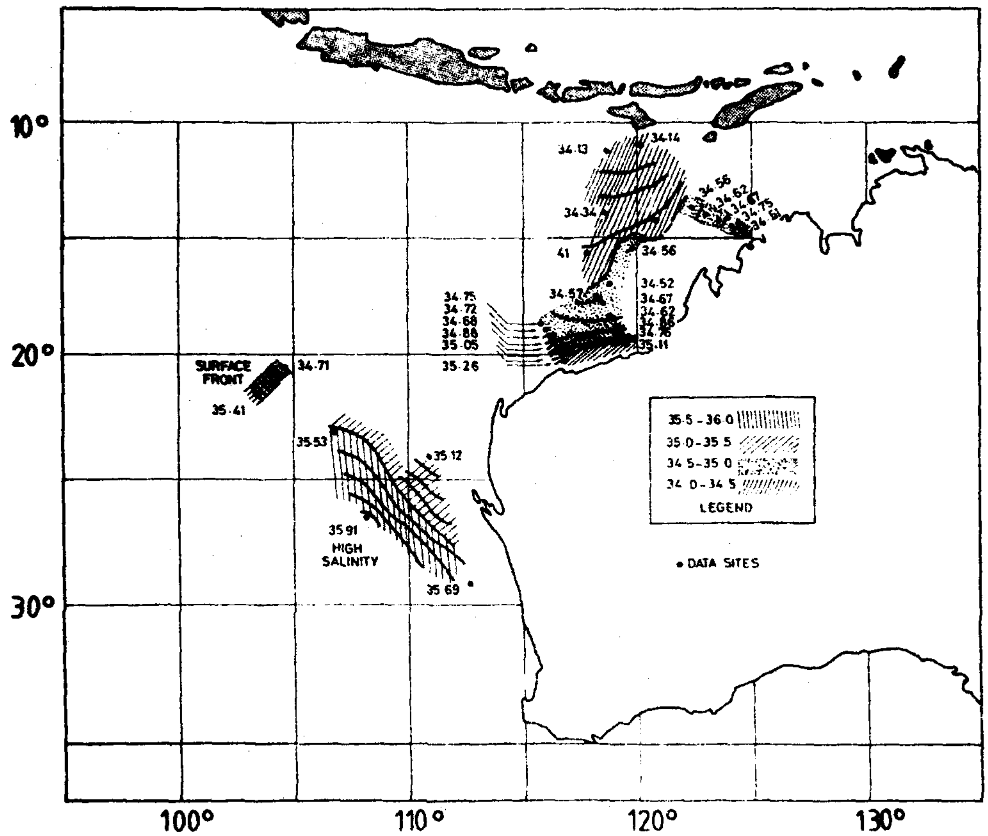

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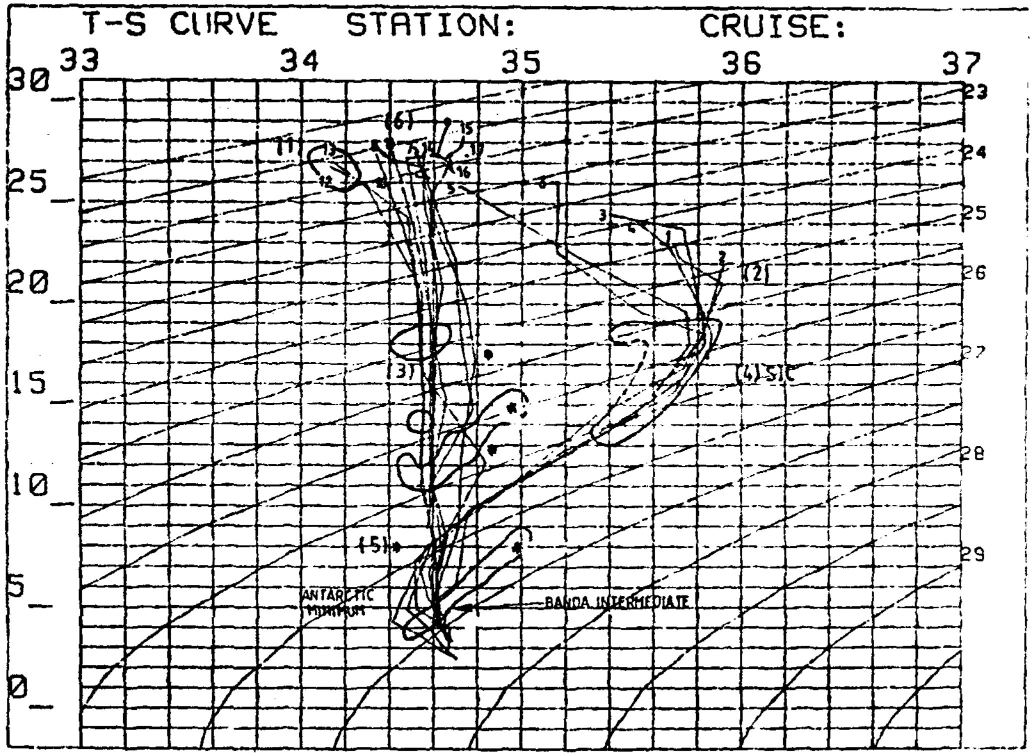

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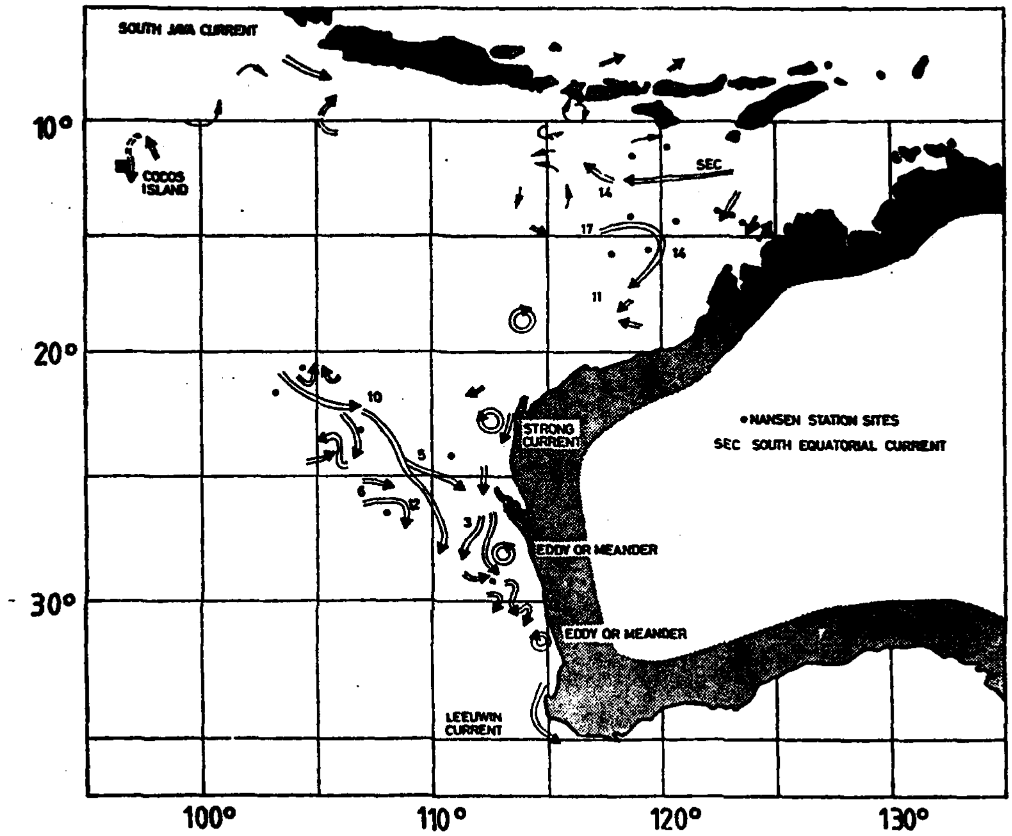

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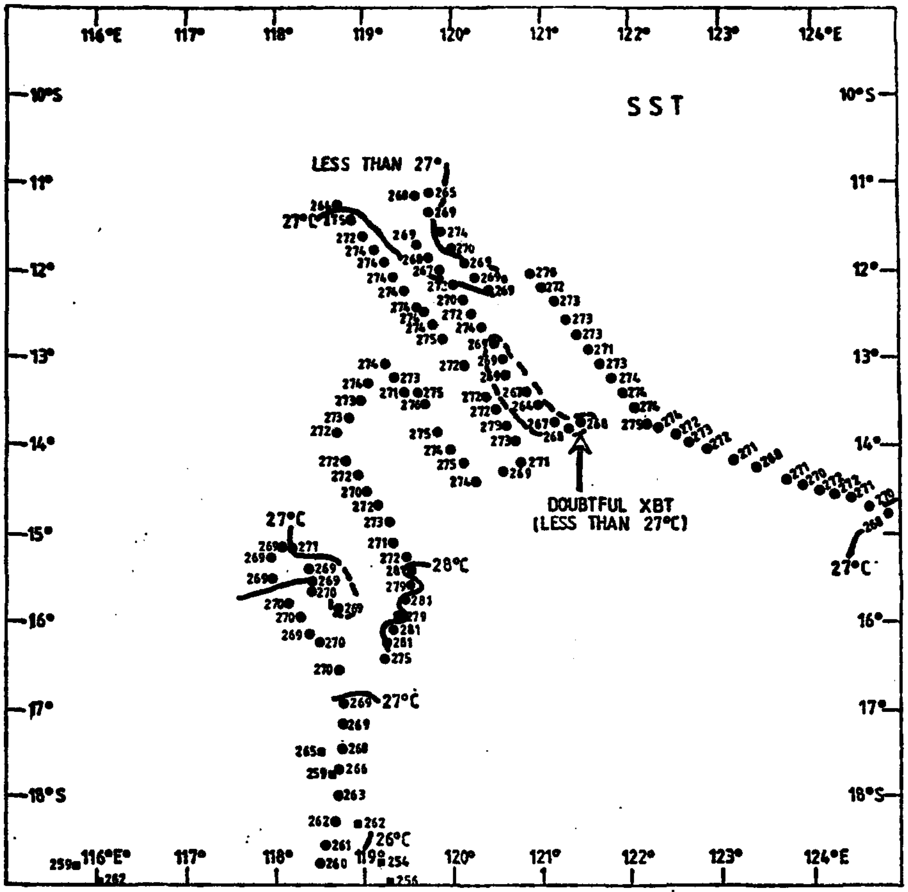
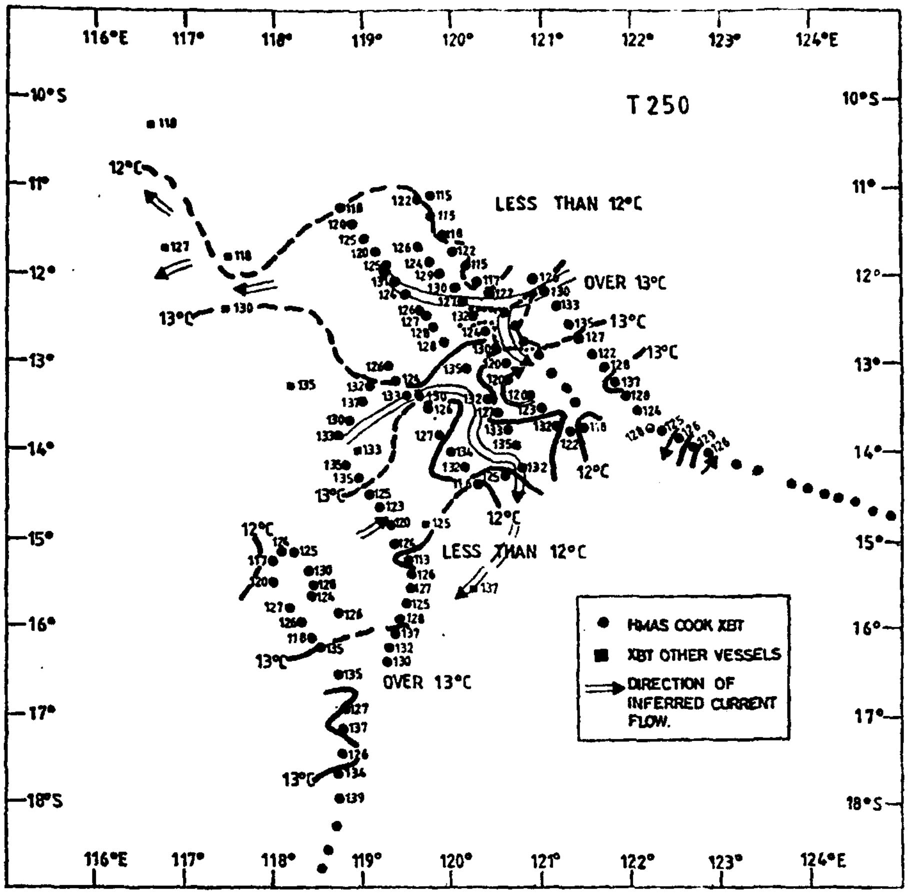


Fig. 9(a) Sea surface temperature contours north-west of Australia drawn from XBT data for June 7-15 1983. See Fig. 3 for further details to the north.



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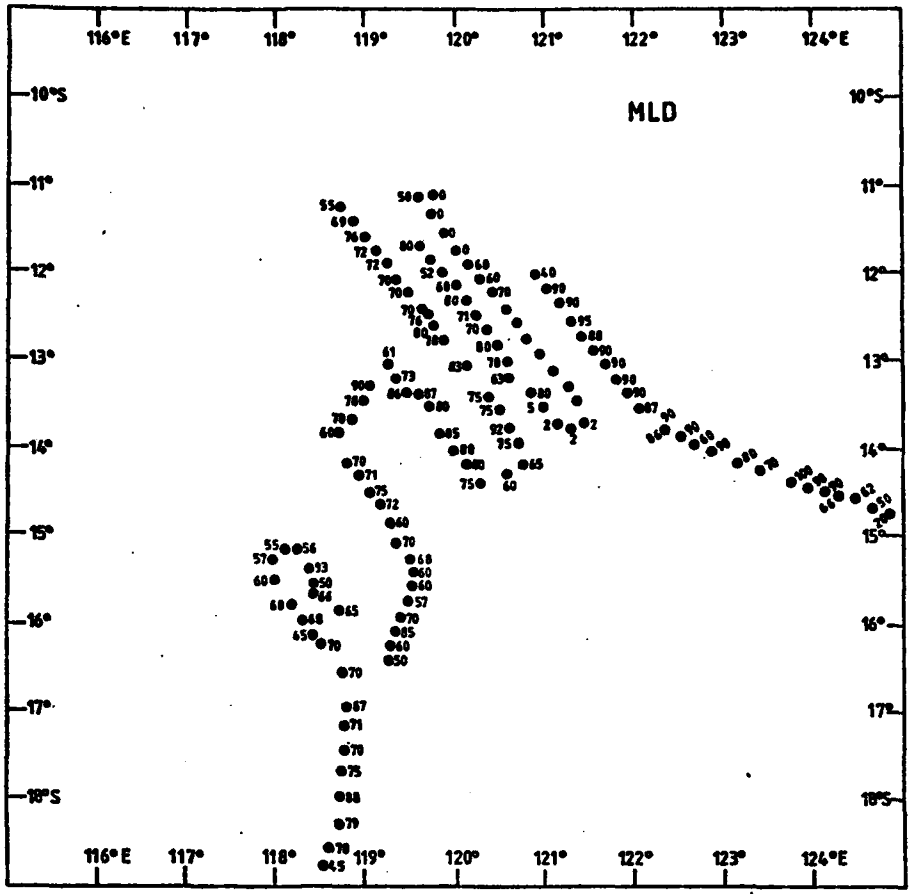

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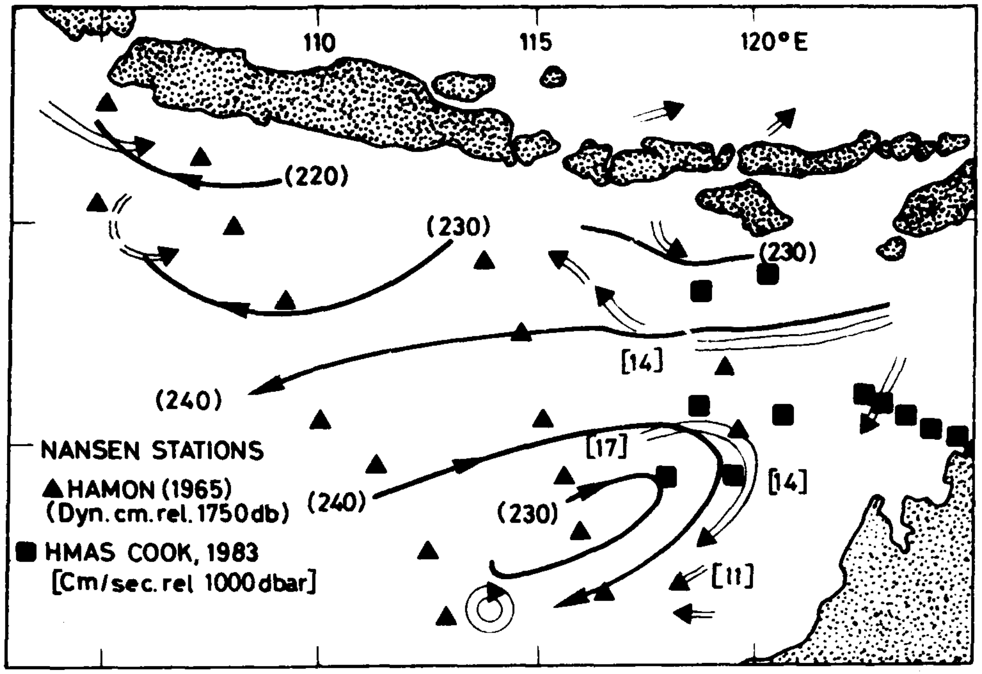

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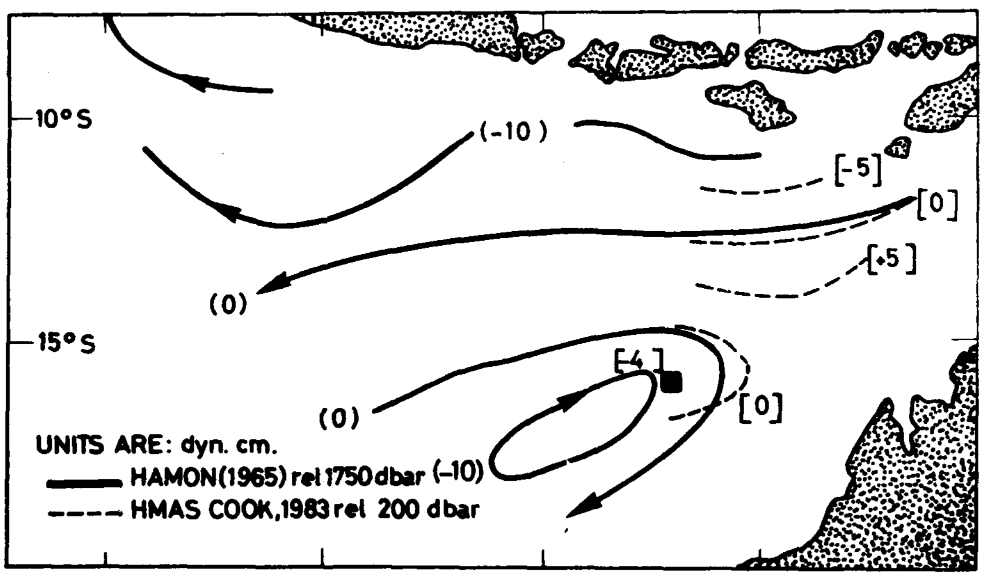

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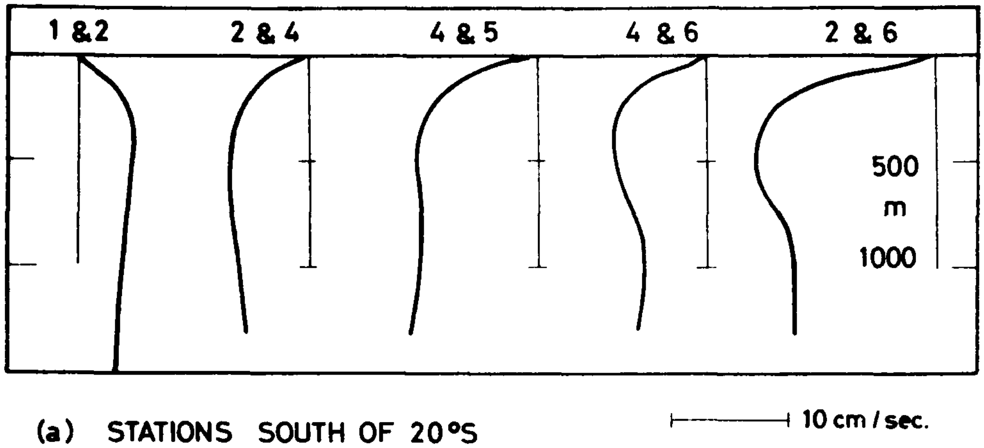
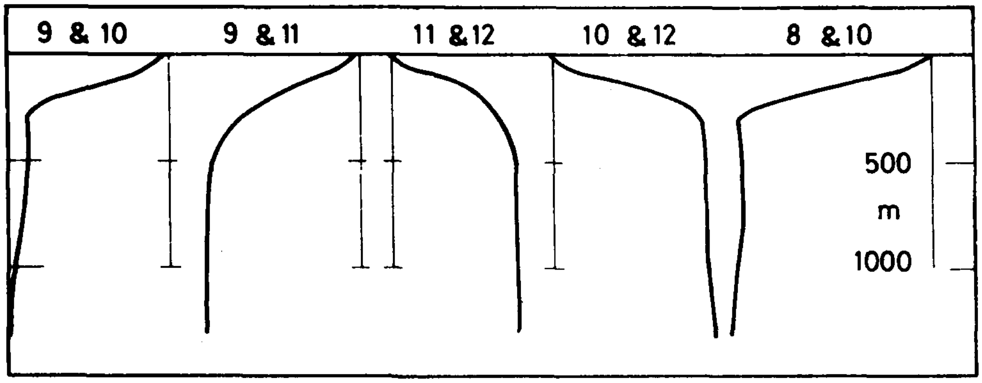
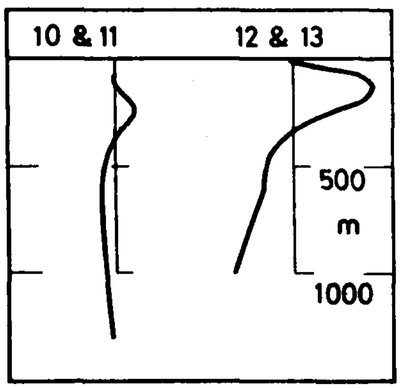


(a) STATIONS SOUTH OF 20°S



(b) NORTHERN STATIONS - NORTH SOUTH SECTIONS



(c) NORTHERN STATIONS
EAST WEST SECTIONS.

Fig. 11

Geostrophic current profiles relative to the surface between station pairs. In the east Indian Ocean for late May and June 1983. Station positions are shown in Fig.2. See Fig.8 for surface current directions.

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16. Abstract

During the period late May to late June 1983 two research vessels and seven ships of opportunity transited sections of the south-east and east Indian Ocean. Expendable bathythermographs were deployed and several Nansen stations occupied, providing a rare occasion of widespread quasisynoptic data coverage for the area. Satellite imagery is available from two sources and three satellite tracked drifting buoys were in the area. Data are used to form a broad scale description of oceanographic conditions for the period, with more detailed analysis possible in the area north-west of Australia. Comparisons are made with data from the Indian Ocean Expedition of early 1960s and other sources. The relation of surface thermal patterns to circulation is examined.